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A SIX-YEAR NUTRIENT BALANCE FOR A CONIFEROUS WATERSHED RECEIVING ACIDIC RAIN INPUTS

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11.1 INTRODUCTION

Biogeochemical fluxes have been studied in two watersheds in the Haute Ardenne region of Belgium, since 1974. The programme of research has been interdisciplinary and involved the fields of ecology, forestry, pedology, climatology, hydrogeology and microbiology. The programme has produced information on the hydrological and ionic fluxes in the system, allowing the construction of accurate nutrient budgets, and it has been possible to evaluate inputs and outputs to the ecosystem without disturbance. These data, together with information on the internal biogeochemical cycles, are necessary to understand and quantify the transfer processes within and through the forests. The methods used and some results are presented here from the flux studies in a spruce-covered (*Picea abies* L. Karst) watershed where forest die-back has been observed.

11.2 MATERIALS AND METHODS

11.2.1 Site Description

The watershed is located in the Haute-Ardenne region of Belgium at about 500m above sea level. The annual rainfall is about 1300mm and the annual average air temperature is +7°C. The study area covers 81 hectares and has the dual advantages of being representative of the Haute-Ardenne region, and also having little lateral water movement. A geological study (Buldgen *et al.*, 1984) has shown that the bedrock is made of phyllade, quartzo-phyllade and quartzite. The water is mostly contained in the deep soil layers and fractured rocks, which

act as permanent source to the brook. The type of bedrock suggests that the loss of water through deep seepage is insignificant.

The soil is an acidic brown earth, originating from pleistocenic loess loam, and characterised by the presence of pseudogleys, with organic layers of the dysmoder type. The pH is usually below 5·0 even in the deeper soil layers, with base saturation being particularly low in the region, fluctuating between 5 and 15 % in the mineral layers (Delecour, 1978).

11.2.2 Vegetation

Norway spruce (*Picea abies*) is the only tree species growing in the watershed, and the trees can be ranked into two age classes: 52-58 and 80-95 years old. There has been no history of coppicing and the ground vegetation is sparse. Many trees are showing symptoms of die-back, with the yellowing and large-scale needle-fall characteristic of the spruce die-back symptoms described for parts of West Germany. Field observations of trees, made in 1986 and compared with observations obtained by infra-red analysis in 1983, showed that more trees were dying in 1986. This agrees with the conclusions of the local forestry administration.

11.2.3 Experimental Design

The water fluxes and their chemical composition were followed at various points in the watershed: (i) in the open field, (ii) under the canopy, as throughfall, (iii) beneath the organic layers, as leachates, (iv) and in the stream at the output of the watershed. Open precipitation and throughfall were collected in rain-gauges made of plastic bottles inserted in a plastic tube and pushed into the ground. Forty rain-gauges were distributed within the watershed, each on a 5 × 5m plot. Such rain-gauges gave the same results as more sophisticated ones, except during snow periods. These rain-gauges are inexpensive, permitting larger numbers of sampling points. It is more useful to increase the number of sampling points rather than the area of individual collectors (Helvey & Patric, 1965). Every rain-gauge plot under the canopy was complemented with a funnel-type lysimeter under the organic layers having an interception area of 285 cm^2. Samples were collected every 15 days.

At the output from the watershed the stream was sampled with an ISCO Sampler Model 1680. The flow was estimated by using a rectangular weir made of 8mm plastic sheet coupled to a limnigraph, or ISCO flowmeter. One sample was taken every 16 hours except in snow periods. Since the ionic concentrations mainly fluctuate during floods (Buldgen *et al.*, 1984), samples were taken when predetermined flow thresholds were met. However, the forecast of flow is difficult to achieve and the best approach appears to be a combination of the two sampling methods.

11.2.4 Chemical Analyses

Water analyses were accomplished using the same methods as described elsewhere (Buldgen, 1982). Samples were analysed for calcium, magnesium, potassium, pH, iron, sulphate, nitrate, phosphate and organic carbon.

11.3 RESULTS AND DISCUSSION

11.3.1 Watershed Budgets

The watershed budgets were calculated from data collected between 1979 and 1983 (see Table 11·1). Wet and dry deposition to the gauge were assessed from the composition of precipitation in the open field. Interception was calculated as the difference between throughfall deposition and open precipitation, with the exception of those ions which seemed to be released by the canopy, namely potassium and phosphate. These latter elements were found to be in significantly larger amounts in the throughfall than in incident precipitation during the growing season. The amount of potassium intercepted during the growing season was calculated from correlations with sulphate and nitrate concentrations computed for the dormant season. It is assumed in this approach that there is no leaching in the dormant season and that the correlations were still valid during the growing season (Buldgen, 1984). For phosphate the ratio between wet and dry deposition for the dormant season was considered to be valid for the growing season (Ulrich *et al.*, 1979). However, these assumptions have yet to be verified.

Table 11.1
Watershed Budgets for the Norway Spruce Forest, Haute-Ardenne, Belgium[a]

	S-SO$_4$	*Inorganic N*	*Ca*	*Mg*	*K*	*P-PO$_4$*	*H*
Wet and dry deposition (1)	19·5	24·5	7·9	2·7	5·0	0·6	1·5
Interception (2)	32·7	11·5	11·4	2·9	14·0	0·1	1·6
Organic layer leaching (3)	53·2	52·0	11·0	4·6	30·0	2·3	3·7
Streamflow output (4)	51·9	14·7	4·0	6·3	3·0	0·1	1·4
Net budget (5)	+0·3	+21·3	+15·3	−0·7	+16·0	+0·6	+1·7

[a] Net budget (5) = (1) + (2) − (4) (kg ha^{-1} year^{-1}).

Interception fluxes calculated in this way do not take account of passive exchange through foliar surfaces, i.e. leaching of internal ions or retention of external ones. Dissolution of dry deposited elements seems to occur within minutes of onset of storm events, being followed principally by passive exchanges (Olson *et al.*, 1985). Our computed interception values are higher than those of Lindberg *et al.* (1986) who compared the sum of throughfall and stemflow with wet and dry deposition to the canopy.

Net balances were calculated as the difference between, on one hand, deposition and interception, and on the other, streamflow outputs (Table 11·1). The net balances show whether the watershed has accumulated or lost constituents

and, consequently, give an indication of potential long term nutrient deficiencies which could occur. Thus, net balance calculations confirmed the observed tree magnesium deficiency symptoms and also suggested a close match between input and output for ~~phosphate and~~ sulphate. The movement of sulphate through the forest was of particular interest because all the fluxes were large, yet little was immobilised. This indicates saturation of the system, and particularly of the soil layers.

Comparison of net balances with estimates of nutrients accumulated in wood (Table 11·2), provides a means of evaluating the importance of output through forest harvesting. Again, it provides an indication of the long-term viability of the form of management. The wood accumulation values were computed from available literature values (Duvigneaud & Denaeyer-de Smet, 1972; Pavlov, 1972) and they confirm the phosphate deficiency status of the ecosystem but, paradoxically, also suggest a sulphur deficiency. Our results indicate that sulphur was absorbed by the needles, as indicated by Tschanz *et al.* (1986) and Mehlhorn *et al.* (1986). However, Weissen *et al.* (1984) have observed in some Belgian diseased forests that needle sulphur content was unaffected.

Table 11.2

Comparison of Net Balances with Rates of Accumulation in Wood (kg ha^{-1} year^{-1})

	S-SO$_4$	*Inorganic N*	*Ca*	*Mg*	*K*	*P-PO$_4$*
Net balance	0·3	21·3	15·3	−0·7	16·0	0·6
Rate of accumulation in wood	5·1	12·3	10·3	2·1	12·3	2·1

Nutrient release from the organic layers was compared with tree absorption (Table 11·3) in order to determine possible limiting nutrients. Tree absorption values were computed from the sum of the tree accumulation values and the litterfall previously evaluated by Parmentier & Remacle (1981). The amounts released by organic layers were underestimated because the first stages of mineral release from litterfall are difficult to quantify. The values in Table 11·3 indicate that magnesium deficiency would not occur, yet it should be remembered that release values were computed for the whole year whereas tree absorption only occurred in the growing season. Such asynchrony would lead to magnesium being leached from organic layers and not being retained in deeper soil layers. This is confirmed by the comparison of release from organic layer (Table 11·3) with stream flow output (Table 11·1).

Table 11.3

Comparison of Organic Layer Leaching and Tree Absorption Rates (kg ha^{-1} year^{-1})

	S-SO$_4$	*Inorganic N*	*Ca*	*Mg*	*K*	*P-PO$_4$*
Organic layer leaching	53·2	52·0	11·0	4·6	30·0	2·3
Tree absorption	9·7	42·0	22·0	3·6	32·1	4·6

In contrast, calcium and phosphate were retained in the organic layers and potassium and nitrate in the mineral layers.

11.3.2 Temporal Variation in Fluxes

As previously mentioned, forest die-back was apparent in the watershed in 1986, though apparently absent in 1983. Since the watershed was monitored over this period, comparison of fluxes through the ecosystem between 1983 and 1986 should provide useful information on the die-back process.

The averages for wet and dry deposition in open precipitation were computed for the April to September periods between 1980-83 and then compared with the rates for the same period in 1986 (Table 11·4). They rarely showed significant differences, except for sulphate and nitrate, which exhibited decreasing trends over that period.

Table 11.4
Mean Values of the Open Rain Deposition Rates Computed for April–September Periods in Different Years (kg ha^{-1} year^{-1})

	1980	*1981*	*1982*	*1983*	*1986*
S-SO_4	28·1	17·5	34·7	19·7	10·6
N-NO_3	14·6	11·3	13·5	8·8	5·8
N-NH_4	13·5	18·6	19·0	14·6	26·6
Ca	18·3	6·9	9·9	6·6	9·5
Mg	4·7	1·8	2·6	1·8	2·2
Na	14·6	6·2	10·6	12·8	15·3
K	6·6	5·1	5·8	4·4	4·0
C org.	21·9	35·4	36·1	51·1	38·0
Fe	0·5	0·3	0·3	0·5	1·2
H	4·0	1·1	2·2	1·8	1·1
P-PO_4	0·5	1·8	0·6	0·4	1·4

The average of the ratios of throughfall deposition rate to open precipitation were compared for the same periods (Table 11·5) using the Waller-Duncan T test (SAS, 1985) after normalisation (Table 11·6). Throughfall rate is the sum of wet and dry deposition to the canopy, plus or minus foliar exchange. By assuming that the canopy density was not modified, it is anticipated that the ratios will reflect the variations of the physiological status of the trees or their responses to changes in deposition rates. It has been shown, for example, that the deposition of acidity influences the leaching of calcium (Kelly & Strickland 1986) or of other ions (Lovett *et al.*, 1985).

For most of the ions, the values fluctuated over the years without any defined trends except for ammonium, sodium and calcium which showed decreases (Table 11·6). These results are of particular interest because ammonium and calcium have been implicated in the die-back process. For ammonium, the decreasing ratio probably reflects increased ammonium absorption by the needles. This phenomenon is particularly severe when the ratio drops to 1, as dry deposition normally occurs at a higher rate on the canopy than in the open field. Van Praag & Weissen (1986) found increased organic nitrogen levels in the needles of diseased trees from the Haute-Ardenne region when compared to healthy trees. Zedler *et al.* (1986) have confirmed this observation and

Table 11.5
Mean Values of the Ratio of Throughfall Deposition Rate/ Open Rain Deposition Rate for April–September Periods in 1981, 1982, 1983 and 1986

	1981	*1982*	*1983*	*1986*
S-SO_4	4·24	1·79	2·72	2·20
N-NO_3	1·98	1·86	1·95	3·52
N-NH_4	1·85	2·12	2·29	1·00
Ca	3·34	2·75	2·20	1·74
Mg	2·58	2·17	1·73	2·35
Na	2·57	1·87	1·38	1·28
K	11·06	6·78	3·95	6·44
C org.	2·52	1·89	1·69	2·67
H	1·76	4·15	15·28	2·07
Fe	1·97	1·28	1·91	1·23
P-PO_4	4·88	5·65	0·90	1·45

Table 11.6
Comparison of the Mean Values of the Ratio of Throughfall Deposition Rate/Open Rain Deposition Rate for April–September Periods in 1981, 1982, 1983, 1986 using the Waller–Duncan T test

	Missing values		*Mean values*			
	Year : number	*Transformation*	*81*	*82*	*83*	*86*
S-SO_4	—	$\log_e x$	1·36^{a}	0·57^{c}	0·82^{b}	0·62^{b,c}
N-NO_3	86 : 11	$\log_e x$	0·63^{a}	0·53^{a}	0·55^{a}	0·35^{a}
N-NH_4	86 : 1	$\log_e x$	0·57^{a}	0·55^{a}	0·11^{b}	−0·06^{b}
Ca	—	x	3·34^{a}	2·75^{b}	2·20^{c}	1·74^{d}
Mg	86 : 6	$\log_e x$	0·90^{a}	0·76^{a,b}	0·39^{c}	0·63^{b}
Na	—	$\log_e x$	0·88^{a}	0·49^{b}	0·20^{c}	0·21^{c}
K	86 : 2	$\log_e x$	2·16^{a}	1·79^{b}	1·17^{c}	1·77^{b}
C org.	86 : 10	x	2·52^{a}	1·89^{b}	1·69^{b}	2·67^{a}
Fe	81 : 6 82 : 16 83 : 8	$\log_e x$	0·53^{a}	0·21^{a,b}	0·56^{a}	0·07^{b}
H	81 : 4	$\sqrt{x}$	1·23^{b}	1·67^{a}	3·60^{b}	1·32^{b}
P-PO_4	81 : 4 83 : 4	$\log_e x$	0·54^{b}	1·25^{a}	−0·99^{c}	−0·13^{d}

The transformation was applied to obtain normal distribution. Values with the same letters are not significantly different at level $P < 0{\cdot}05$.

attributed perturbation of nitrogen metabolism partly to an abnormal uptake of ammonia by the needles, but also as a consequence of soil acidification inhibiting nitrate (but not ammonium) uptake. For calcium, the decrease in the ratio could be the result of a decreasing needle content following an inhibition of root absorption. This hypothesis is supported by higher calcium concentrations as recorded in the brook. Moreover, a number of investigators have demonstrated calcium deficiencies in the needles of declining firs and spruces. Such deficiency

would occur as a result of calcium and magnesium washout, whilst release of aluminium in the soil would have detrimental effects on plant growth through an inhibition of calcium absorption (see Kohlmaier *et al.*, 1984).

Finally, the mean ionic concentrations in the brook were calculated for the periods April to September in 1980-1981, 1982 and 1986 (Table 11·7). Most of the differences were statistically significant. Several factors have to be considered before interpreting these results; (i) the yearly streamflow variation, (ii) the sampling programme, and (iii) the sampling method. The sulphate, nitrate, sodium, potassium, iron and organic carbon concentrations were positively correlated with streamflow, whilst calcium and magnesium concentrations were negatively correlated. It was concluded that sulphate concentrations had decreased in 1986 compared to 1980-1981 or to 1982, and that calcium and magnesium concentrations had increased in 1986 compared to 1980-1981. No correlation with streamflow was found between either H ions or phosphate concentrations.

Table 11.7
Mean Values of the Ionic Concentrations in the Brook for April–September Periods in 1980–1981, 1982 and 1986 (mg litre^{-1}) and mean streamflow at sampling time ($m^3\,h^{-1}$)

	1980–1981	*1982*	*1986*
Streamflow	36·2	30·9	55·0
S-SO_4	9·23^a	8·43^a	5·21
N-NO_3	2·04	1·63	2·76
Ca	0·56	1·00^a	1·53^a
Mg	1·19	1·31^a	1·31^a
Na	3·18	3·05	3·61
K	0·49	0·38	0·54
C org.	8·04	7·16	10·04
H	0·38	0·19	0·23
Fe	0·18^a	0·18^a	0·44
P-PO_4	0·019	0·013	0·038

Values with the same letters are not significantly different at level $P < 0{\cdot}05$.

In addition, an increase in phosphate concentrations was obvious in 1986. It was assumed that (i) the increasing calcium, magnesium and phosphate concentrations could be related to declining tree root absorption due to the die-back, and (ii) that the decreasing sulphate concentration could be the response to the declining deposition rate for this system which is saturated with sulphate.

11.4 CONCLUSIONS

The watershed approach shows how a forested ecosystem responds in the presence of atmospheric pollutants. It is well exemplified by considering the calcium and sulphate transfers through the components of the forest, from the open rain to the brook.

The brook provides the main reference point because of the reliability of the recorded data, in comparison with the difficulties associated with obtaining accurate estimates of total input values. It can be inferred from the preliminary data that calcium absorption would be reduced and could to some extent explain the forest decline. Consideration of the sulphur balance results in two main conclusions. Firstly, sulphur enrichment of precipitation occurs in the canopy and, secondly, it seems that mineral horizons are saturated, since the sulphate input closely parallels output. These preliminary results need to be confirmed by further observations extended over several more years.

11.5 SUMMARY

The nutrient budget of a coniferous watershed (81 ha) has been studied for six years. The watershed is located in the 'Haute-Ardenne' region (Belgium) at about 500m above sea level.

The following forest components were examined: precipitation, throughfall, leaching from the organic layers and output in streamflow. The analysis of the transfers of water and mineral elements through the forest, to the brook, indicates the influence of biotic and abiotic components on water chemistry and indicates how an ecological system may respond to environmental stresses. It is mainly exemplified by the comparisons of nutrient balances drawn up for a succession of years spanning the onset of forest decline in the watershed.

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